THE ULTIMATE SHEAR STRENGTH AND SHEAR FATIGUE OF HUMAN CORTICAL BONE

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Introduction

We hypothesized that bone fails in tension when subjected to transverse shear stress. Shear strength of bone is commonly determined by torsion tests. However, the fracture surface produced by a torsional load is helical in nature, and typically corresponds to the plane of maximum tensile stress. We examined our hypothesis by testing human cortical bone specimens in both longitudinal and transverse pure shear and compared the failure stresses and fracture patterns.

We also hypothesized that human bone has shorter fatigue life under longitudinal shear than under tensile or compressive loading. Bone is weak in shear and longitudinal shear stresses may create bone microdamage. We tested the hypothesis by performing longitudinal shear fatigue tests on human bone specimens.

Methods

Transverse and longitudinal shear tests were performed by loading human cortical bone specimens to fracture. The bone specimens were obtained from the cortex of femora from 4 donors (3 males aged 63, 72, 74 and 1 female aged 83). Ultimate Shear strengths in the transverse (n=11) and longitudinal (n=13) directions were measured using Iosipescu and Arcan pure shear test fixtures, respectively. These test configurations produce pure shear stress in the critical region of the specimens. Unpaired t-test was performed to compare the ultimate shear strength in the transverse direction with that in longitudinal direction.

The shear fatigue tests were performed by subjecting human bone specimens (n=16) to cyclic longitudinal shear loading using the Arcan fixture. The bone specimens were obtained from the cortex of femora from 2 donors (males aged 63 and 72). First, one specimen from each group was loaded to fracture to determine the ultimate longitudinal shear strength for that group. Then the rest of the group were tested under cyclic load with four shear stress levels which were 60%, 70%, 80% and 90% of the ultimate longitudinal shear strength determined by the first test. The specimens were randomly selected for different stress levels. Testing was conducted at 2 Hz in load control using an MTS machine. Cycles to complete fracture were recorded. Least squares regression was used to analyzed the fatigue test results.

Results

The longitudinal shear strength (51.64±1.89 MPa) of human bone was significantly less (p=0.0002) than the transverse shear strength (65.30±2.43 MPa). All the specimens in the transverse shear test fractured at a 45° angle from the shear plane. The typical fracture pattern in the longitudinal shear test specimens was straight fracture across the critical region, which corresponded to the shear plane.

Fatigue results are summarized in stress vs. cycles to failure relationship (S-N curve). The S-N relationship can be expressed as:

$$S = A \cdot \log N + B$$

$$S = \frac{s}{s_{ult}}$$

Where A and B are constants. S is normalized stress level, which is expressed as a percentage of the ultimate longitudinal shear strength for the corresponding group. The calculated value of A was –0.097, and the value of B was 1.015 (R^2=0.922).

Discussion

All the specimens in the transverse shear test failed in the principle tensile plane that is 45° from the shear plane. The estimated ultimate tensile strength in 45° off-axis direction is 73.73 MPa and ultimate shear strength measured in torsion tests in the literature is 68 MPa [1]. It appears that bone specimens failed in 45° off-axis tensile stress instead of in shear stress in the transverse shear tests. We feel that longitudinal shear test is the proper method to determine the shear strength of cortical bone. Transverse shear or torsional tests may over-estimate the shear strength of cortical bone.

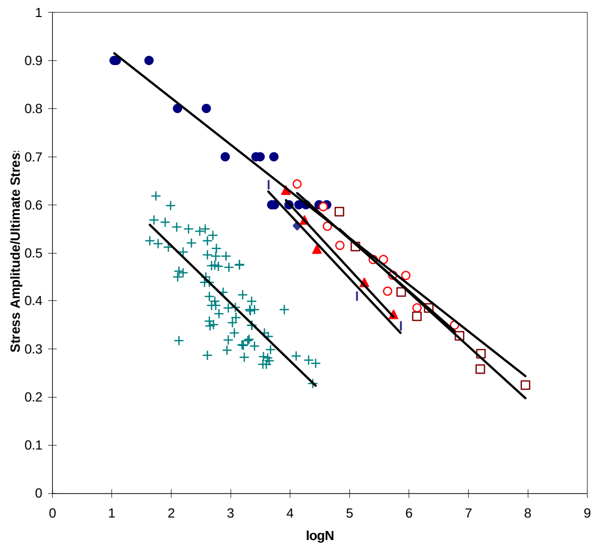

Figure 1. Comparison of normalized stress vs. cycles to failure in fatigue studies. ❍, Swanson et al. (1971), human, rotating bending [2]; ◆, Lafferty and Raju (1979), bovine, rotating bending [3]; ▲, Carter et al. (1976), bovine, rotating bending [4]; □, King and Evans (1967), human (embalmed), rotating [5]; ✚, Carter and Caler (1981), human, uniaxial [6]; ●, current study, human, pure longitudinal shear.

We compared the shear fatigue data with the fatigue data from other studies by normalizing the stresses using the ultimate tensile strength reported in the literature[1]. The regression curve for the shear fatigue data of the current study fits very well with all of the fatigue data obtained from rotating bending tests. An exception is the data from Carter and Caler (1981) which were collected in fully reversed uniaxial tensile and compressive tests rather than rotating bending. Our data also suggests that a universal fatigue failure criterion can be developed for shear and bending loading modes.

References

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